

PALE BLUE DOT II – SESSION 3 – TALKS AND DISCUSSIONS --
MARTENS, VISSCHER, CONRAD, DES MARAIS; GENERAL
DISCUSSION

Martens, opening comments. We need to provide a list of websites for the newcomers to “Pale Blue Dot” research, especially students and non-science majors who will perform the future research and/or provide public support. Informative illustrations and images also must be available on these websites.

Regarding the recent revolution in biogeochemistry: One major advance in our understanding has been based upon the realization that life takes advantages of practically all energy sources (“energy niches”). The synergy between microbes is important and is finally being addressed substantively. The importance of interdisciplinary research has also been recognized in the form of real funding for such projects. The genetics research revolution has also had an impact upon biogeochemistry. Organic geochemistry has matured to investigate the relative reactivity of organic compounds, their burial efficiency, and their reactions at interfaces, be they physical (e.g., air-water, water-sediment), chemical (e.g., oxygenated versus sulfidic) and biological (e.g., transport of various species across cellular membranes). Quantitative models that consider the constraints of physical diffusion and chemical reactions are becoming ever more sophisticated.

Key questions to address in this session include the following: Looking at Earth from 10 parsecs away, what kinds of chemical disequilibria must be present to indicate the presence life? What have been the roles of geologic processes upon determining the trajectory of biological evolution?

Visscher talk. We can link physics to biology by considering the laws of thermodynamics, which, of course, life must obey. Systems strive to chaos, but life is highly organized, therefore it takes energy to stay alive. Light is a very important source of energy for our biosphere, but in environments where light is not available, oxidation/reduction (redox) reactions provide chemical sources of energy. Coupling of reactions facilitates this, and such reactions are typically connected by and ultimately linked to the creation and consumption of protons. The proton gradient across membranes sets up the energy resource that fuels ATP production. Many examples can be given (such as sulfur and nitrogen transformations, and methanogenesis) that contribute to the maintenance of proton gradients. Organisms can differ from each other, not only in the reactions in which they specialize, but also their particular biochemistry and how rapidly they can utilize substrates over a range of concentrations. Some previously-unsuspected organic substrates might be particularly important, e.g.,

acetone. Regarding biogenic volatile gases, sulfur compounds (e.g., mercaptans, DMS) play an important role. To understand properly their abundance in nature, we must consider both their production and consumption. Clearly these compounds can be produced both biologically and abiotically; but how can we recognize the differences? Many key reaction mechanisms involve both biological and nonbiological steps (e.g., Charlson's models for sulfur gases that are biologically produced and are then oxidized nonbiologically). We can find biological pathways that link many of these sulfur species, so the next big challenge is to estimate both the rates and importance of these pathways in nature. Environmental fluctuations are important for understanding gas outputs. We must therefore perform time-course experiments to understand both the biological and environmental controls on gas production. One highly productive approach has been to document the performance of microbial mat communities during a 24-hour daily cycle. Preliminary observations of gas emissions at Yellowstone (Angel Terrace) reveal the production of biologically-distinctive gases (methyl mercaptan, mercapto-acetate). Such production becomes substantial once the temperature falls to the point where cyanobacteria become prominent. By defining the performance of microbial communities over a range of environmental conditions, we should be able to achieve a better understanding of life's contributions to the early atmosphere of Earth, and, perhaps, the atmospheres of distant planets.

R. Conrad talk. Microphotographs of methanogens show rather monotonous shapes. Even the physiology is remarkably straightforward, however much of this physiology is probably very primitive. They represent a very primitive form of primary production from C_1 compounds. The reduction of methyl coenzyme M is the central reaction for energy production. From the perspective of their rRNA phylogeny, the various groups of methanogens are more divergent from each other than are animals from fungi. In addition to CO_2 , methanogens can utilize some organic carbon substrates, e.g., acetate and methanol, in the absence of O_2 . Many of these transformations are made possible because methanogens work in concert with other microorganisms, for example, those that ferment carbohydrates to produce H_2 . Methanogens are tied very closely to environmental levels of H_2 . They can draw down H_2 levels and thus make H_2 -yielding reactions more favorable for other microorganisms. The thermodynamic conditions observed in nature where methanogenesis occurs are very close to providing the minimum energy needed by the methanogenesis for ATP production. Methanogens live in very close association with the bacteria that provide H_2 . Today, with O_2 in the

atmosphere, methanogens are restricted to local anaerobic environments. Furthermore, the presence of sulfate and ferric iron can inhibit methanogenesis. Also, the CH_4 they produce is commonly consumed by aerobic reactions, which greatly reduce the amount of methane that enters the atmosphere.

Des Marais talk. One key objective is to develop a set of principles that guide a search for life beyond our own solar system and are not just relevant to studies of our own early biosphere. Life arose very early on the Earth; this has obvious implications for extrasolar system life because it indicates that life can arise relatively quickly and therefore might have arisen many times in the universe. Early morphologic fossil evidence (e.g., stromatolites and cellular remains at 3.46 Ga) gives satisfying evidence of life's presence, but tells us little about what life was doing (e.g., gas production), which of course is a topic of great relevance to this workshop. Of life's three basic functions, namely information storage and replication, energy harvesting, and biomass synthesis, energy harvesting and biomass synthesis are most relevant to the subject of atmospheric effects. The chemical products of energy harvesting are important. The sheer abundance of organic material and its burial also have affected the atmosphere. Life plays key roles at the major environmental interfaces, etc. between solid earth, oceans and atmosphere. Life is an excellent catalyst for organic chemistry, and it enhances weathering (levels of soil CO_2 and organic acids). Life has maintained a redox disequilibrium between buried organic carbon and sulfide and oxidized products in the oceans in the atmosphere. Life's ability to maintain monotonic directionality in its evolution is a property that sets it apart from nonbiological chemical transformations. The rRNA "geneological tree of life" illustrates this. This tree helps us to infer those characteristics of life that are more universal and therefore might be more ancestral and ancient. We can perhaps infer the sequence of events in evolution and therefore chart the nature of the energetic harvesting processes that might have been most important at various stages in earth history. The uptake of CO_2 and the utilization of H_2 seem very ancient. Photosynthesis clearly came later but it certainly became prominent as a driver of global primary production when O_2 -yielding photosynthesis arose. The advent of each of these successive stages increased the repertoire of capabilities by which life could impact the composition of ancient atmospheres. Prior to 3 billion years ago, life was already photosynthetic, it could utilize sulfide, and it was widespread in coastal environments and thus could cope with desiccation and UV stressors. Life was indeed was sophisticated at the beginning of the

well-preserved geologic record some 3.5 billion years ago. There are multiple lines of evidence (morphological, geochemical, phylogenetic, and environmental) that are consistent with the possibility that oxygenic photosynthesis arose prior to 2.5 billion years ago. Even if oxygenic photosynthesis did not lead immediately to the accumulation of atmospheric O₂, the greatly enhanced global productivity could have led to the emission of a host of reduced biogenic species that sustained detectable atmospheric components. One challenge to this research program will be to define what these volatile organic species were. The atmosphere became substantially more oxidized relatively abruptly about 2.1 Ga ago, and it is important to understand why. The advent of oxygenated environments probably contributed to the eventual development of multicellular life. In summary, rocky (Earth- and Mars-like) planets share very similar histories early in their history, during a time interval within which life first arose on Earth. Thus parallels in the geological evolution of planets can help us to infer how life might have arisen and evolved elsewhere.